Passive Devices for Axisymmetric Base Drag Reduction at Transonic Speeds

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Experiments have been made to assess the effectiveness of several base modifications or passive devices for reducing base drag and total afterbody drag at transonic speeds. The modifications tested include base cavities, ventilated cavities, and two vortex suppression devices. Results show that, while appreciable base drag reductions are possible with many of the devices examined, the net total drag reductions are relatively lower, presumably because of the additional losses associated with the devices.

Nomenclature

A	=	forebody (max) cross-sectional area, $=490.625$ mm^2
A_v	=	total area of ventilation
C_{DA}	=	total afterbody drag coefficient, = net drag force/$q_\infty A$
C_{pb}	=	base pressure coefficient
D	=	forebody (max) diameter, = 25 mm
h	=	cavity depth
L	=	afterbody length
M_∞	=	freestream Mach number
q_∞	=	freestream dynamic pressure
t	=	cavity lip thickness
β	=	boat-tail angle
δ^*	=	boundary-layer displacement thickness

Introduction

THERE is considerable interest in exploring new methods of reducing various forms of drag with a view toward improving the aerodynamic efficiency of flight vehicles. Flow separation, often difficult to avoid in practical situations, generally leads to an increase in drag, and separation control by some active or passive means would be beneficial. Base drag, arising from flow separation behind blunt bases, can be significant in connection with missiles, projectiles, aircraft afterbodies, etc.

In the two-dimensional case, several techniques, for example, base bleed, boat-tailing, wake vortex suppression devices (VSD's), and base modifications, are known to offer significant reductions in base drag at subsonic and transonic speeds.[1] Any method that suppresses or delays vortex shedding in two-dimensional flows generally leads to an increase in base pressure and a consequent reduction in base drag. Of the methods for axisymmetric base drag reduction, the effects of boat-tailing and base bleed are well known.[1] The vortex shedding process is relatively less pronounced in axisymmetric flows. It is rather unclear in contrast with two-dimensional (2D) flows whether vortex suppression devices, either in the near wake or through base modifications, can be effective base drag reduction devices.

Compton[2] investigated the effects of base recessing and base concavity of boat-tailed bases and found small base drag reductions at subsonic and transonic speeds. The base modifications (to act as VSD's) studied by Gai and Patil[3] resulted in a noticeable increase in base drag, unlike its 2D counterpart. Morel's[4] systematic study at low speeds showed the beneficial effects (on base pressure and drag) of base cavity, a single type of ventilatled slot, and slit geometry. From the available literature, it appears that methods for axisymmetric base drag reduction, other than by employing boat-tailing or base bleed, have not been explored sufficiently nor has the usefulness of some of the 2D concepts been assessed. Furthermore, very little information exists at transonic speeds, where the base drag penalty is generally higher than at subsonic speeds.

In this paper, an assessment is made of the effectiveness of different base modifications or passive devices for reducing base and total afterbody drag at transonic speeds. The base modifications investigated include 1) cavities, 2) ventilated cavities with different ventilation geometries, and 3) two vortex suppression devices. Typical effects of these devices on boat-tailed and flared bases have also been assessed.

Experiments

Experiments have been performed in a 38 × 30 cm transonic wind tunnel in the Mach number range of 0.7–1.0. The freestream Reynolds number (based on the model length of 30.5 cm, Fig. 1) varied between 8 and 9.5 × 10^6 in the preceding Mach number range.

A sketch of the model support system, along with the afterbody model and the drag balance, is shown in Fig. 1. The metric part consists of a fixed cylindrical section 30 mm long and a removable afterbody typically 100 mm long (Fig. 1). The balance measures the total axial force (drag) experienced by the metric part of the model. Total drag measurement facilitates direct assessment of net drag reduction and automatically includes the effects of three-dimensional (3D) flow variations, if any, resulting from the base modifications. Base pressure is measured at a single location on the model centerline. All tests were carried out at zero incidence. The model boundary layer was also tripped in the nose region at a distance of 25 mm from the apex.

Table 1 shows the details of various afterbody models with base modifications; these may be classified under base cavities (configurations A1–A5, D1, F1), ventilated cavities (configurations B0–B4, C1, C2, D2, F2), and vortex suppression devices (configurations E1 and E2). A cylindrical afterbody 100 mm long (Fig. 1) is used as a baseline configuration for assessing base and total drag reductions. Similarly, for the assessment of D1, D2 and F1, F2, corresponding (unmodified) boat-tailed and flared bases are utilized.

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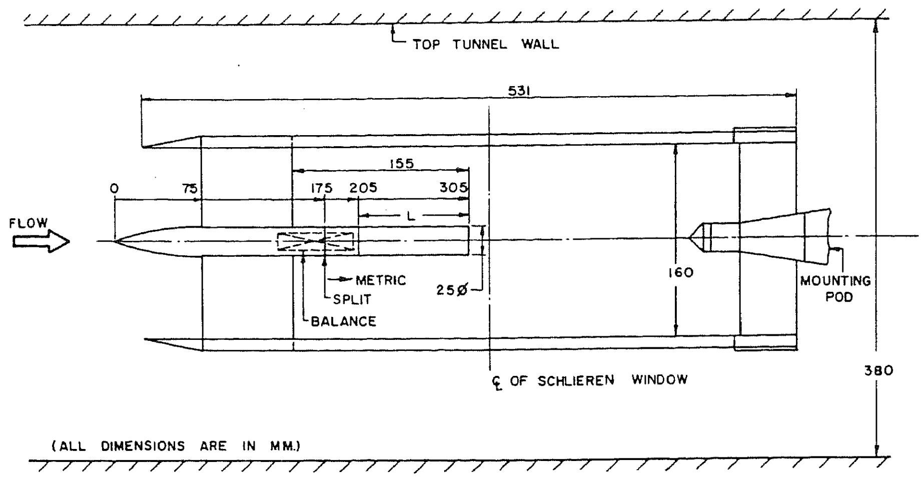

Fig. 1 Model and support system.

Table 1 Details of afterbody models with base modifications

CONFIGURATION	ID	L	h	t	d_1	CONFIGURATION	ID	L	h	t	d_1	CONFIGURATION	ID	L	h	t	d_1
D=25	A1	110	10	1·75		NO. OF SLOTS: 8*	B4	110	10	1·25		NO. OF SLOTS: 8*	D2	107·5	7·5	1·0	
	A2	107·5	7·5	1·75													
	A3	105	5	1·75													
	A4	110	10	1·25													
	A5	110	10	3													
NO. OF HOLES: 12*	B0	105	5	1·25	2·0	NO. OF HOLES: 8*	C1	105	5	1·75	2	NO. OF NOTCHES: 12*	E1	105	5	1·75	
	B1	105	5	1·25	2·85		C2	105	5	1·75	3						
NO. OF SLOTS: 4*	B2	105	5	1·25			D1	107·5	7·5	1·0			E2	105	5	1·75	
NO. OF SLOTS: 8*	B3	107·5	7·5	1·25			F1	107·5	7·5	1·5		NO. OF HOLES: 12*	F2	107·5	7·5	1·5	3

ALL DIMENSIONS ARE IN MM
* SPACED UNIFORMLY AROUND CIRCUMFERENCE

Tunnel stagnation pressure was measured accurately with a 150-psia transducer. Two 5-psid transducers were employed to measure the differences of the freestream static pressure to the base pressure and freestream static to the split pressure. Uncertainty in drag measurements was within $\pm 3\%$ of C_{DA}.

Results and Discussion

Results of the base pressure coefficient, C_{pb}, and total afterbody drag coefficient, C_{DA}, for various configurations shown in Table 1 are presented in Figs. 2–10. The forebody sectional area A is used for defining C_{DA}.

Base Cavities

Results for base cavities (A1–A5) are displayed in Figs. 2 and 3, bringing out clearly the effects of cavity depth h and lip thickness t on C_{pb} and C_{DA}. Both base and total drag show a monotonic decrease with h/D, except at $M_\infty = 1$. At low speeds,[4] there is some evidence that the optimum value of h/D for minimum total drag occurs around 0.35. From the present data at transonic speeds it may be tentatively concluded that the optimum h/D is likely to occur beyond $h/D = 0.4$. It would be of interest to determine the optimum cavity depth in future experiments. It is interesting to note (Fig. 3) that there is also an optimum value for the lip thickness ($t/D = 0.07$–0.08) even though the t/D range is relatively small; this optimum value corresponds to about $3\delta^*$ at separation.

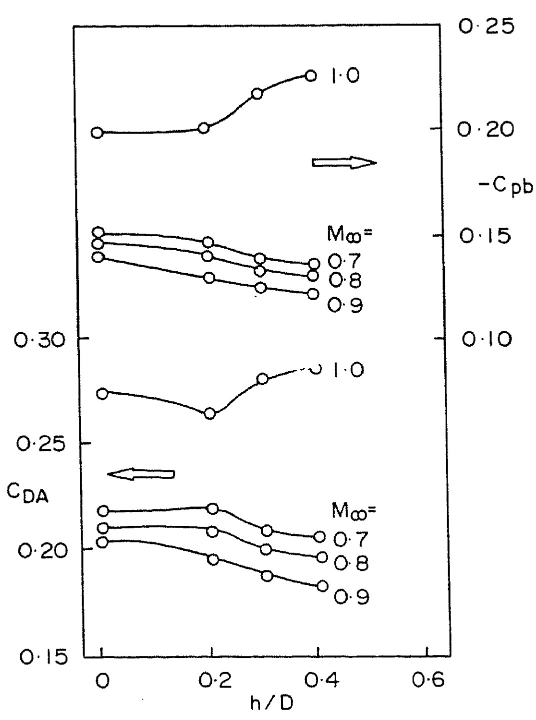

Fig. 2 Effects of cavity depth.

Ventilated Cavities

Effects of ventilated cavities (B0–B4, C1, C2) are shown in Figs. 4–6. Ventilation provides a natural bleed of air into the base region, augmenting the base pressure. The beneficial effects on base pressure and drag seem comparable to the cavity effects.

Figure 7 shows a correlation for the increase in base pressure ΔC_{pb} (from the value for the cylindrical base) due to the ventilated cavities discussed previously. The vertical bar

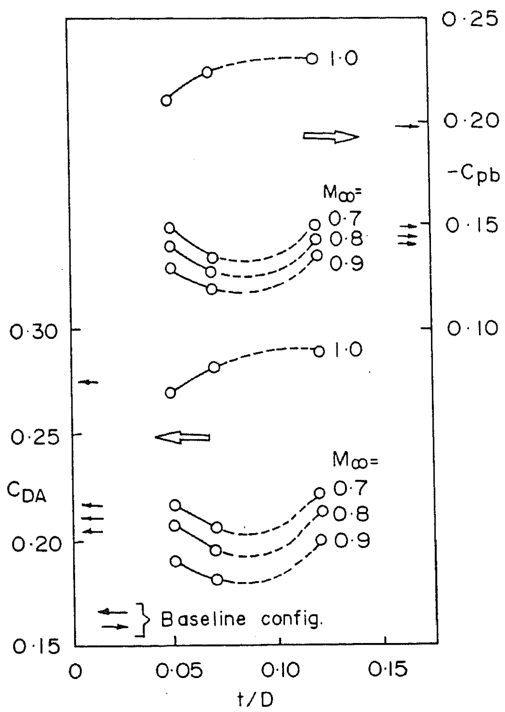

Fig. 3 Effects of cavity lip thickness.

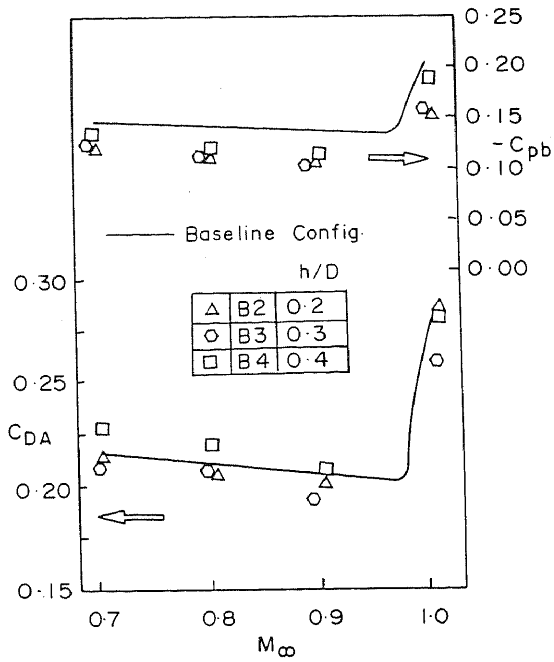

Fig. 5 Effects of cavity ventilation: configurations B2–B4.

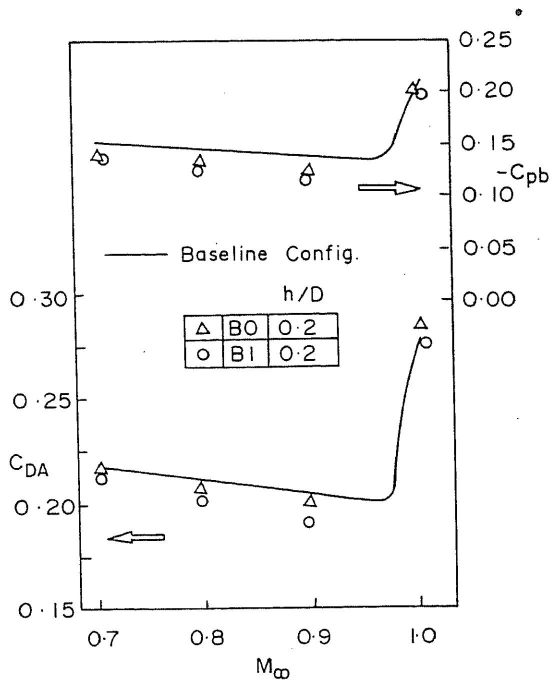

Fig. 4 Effects of cavity ventilation: configurations B0 and B1.

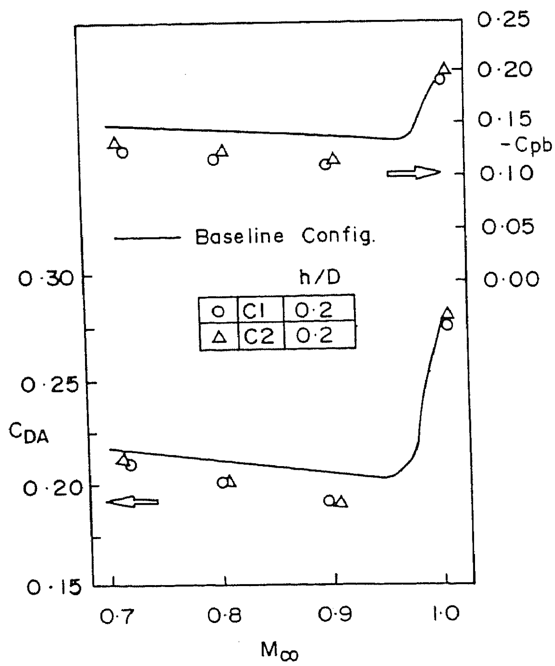

Fig. 6 Effects of cavity ventilation: configurations C1 and C2.

represents, for each configuration, the variation of ΔC_{pb} in the M_∞ range $0.70 \le M_\infty \le 0.90$. The correlation of ΔC_{pb} with A_v, the total ventilated area, suggests relatively weaker effects of cavity depth, ventilation geometry, etc., in determining the base pressure. In an approximate sense, A_v is also proportional to the total bleed mass flow in this narrow M_∞ range. The improved effects of inclined bleed holes (configurations C1 and C2) may be clearly seen; this increased effectiveness is likely to result from the reduced losses in the streamwise momentum of air while passing through the inclined bleed holes compared to holes normal to surface (e.g., B0, B1). More data are desirable to validate the usefulness of this correlation, particularly at higher values of A_v/A.

The total drag reductions due to ventilation, on the other hand, do seem to depend on cavity dimensions and ventilation geometry (Figs. 4–6); shorter cavities with small amounts of ventilation seem preferable.

Vortex Suppression Devices

Results for the two VSD's are shown in Fig. 8: Configuration E1 is the axisymmetric counterpart of a 2D notch or a serrated trailing edge; configuration E2 has a highly irregular (three-dimensional) separation edge. Both were designed to destabilize or interfere with the (admittedly less pronounced) vortex shedding process in these configurations. Both devices seem quite effective in increasing the base pressure, except at $M_\infty = 1$. The changes in base pressure are noticeably higher than would be expected due to cavity alone in these configurations (see configuration A3, Fig. 2). The net drag reductions, however, are relatively less than those obtainable from cavities with or without ventilation.

Boat-tailed Base with Cavity and Ventilation

Effects of cavity and ventilation for a conically boat-tailed base ($\beta = 5$ deg) are illustrated in Fig. 9. The solid lines represent results for an (unmodified) boat-tailed base with the same β and base diameter as D1 and D2. Both cavity and ventilation seem to have little effect; apparently, boat-tailing has a much stronger effect in altering the near-wake properties than the base modifications examined here.

Flared Base with Cavity and Ventilation

In contrast with the results for the boat-tailed base, both cavity and ventilation have strong favorable effects on base pressure and total drag for the flared case (Fig. 10). This is perhaps not surprising since the base drag penalty for a flared base is generally much higher, both because of higher base area and lower values of base pressure, in comparison with a cylindrical base.

Performance of Devices

Base and net drag reductions relative to appropriate baseline configurations are illustrated in Figs. 11–13 for some of the promising configurations discussed previously. While there is no ambiguity about the magnitude of the net aft-body drag reduction (in view of direct measurement), some assumptions seem necessary to estimate the reduction in base drag. For axisymmetric bases, there is evidence[4] from investigations at subsonic speeds that variations in base pressure of 5–10% can exist across the radius, with the minimum value on the centerline. With cavity and ventilation, the situation can be very different. Morel's[4] results show negligible base pressure variation for cavities with $h/D > 0.20$ and larger nonuniformity for ventilated cavities. For the estimates shown in Figs. 11–13, measured centerline base pressure is assumed uniform across the base.

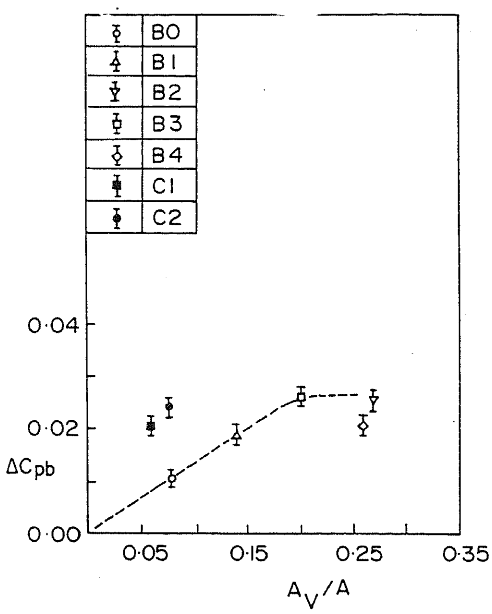

Fig. 7 Correlation of base pressure with ventilation.

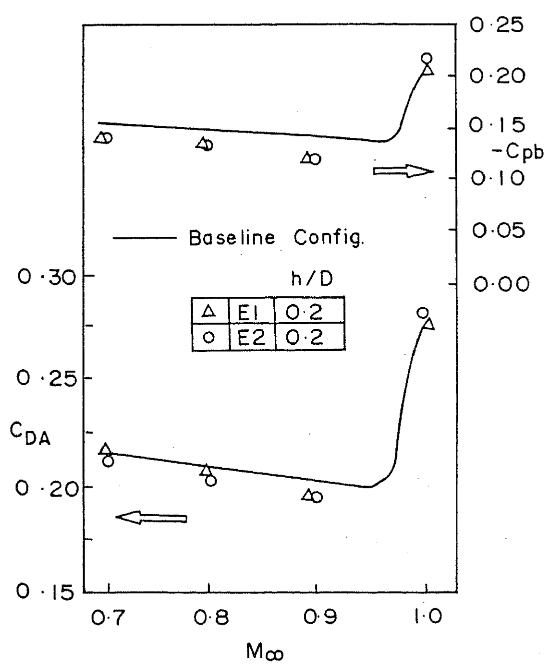

Fig. 8 Effects of vortex suppression devices.

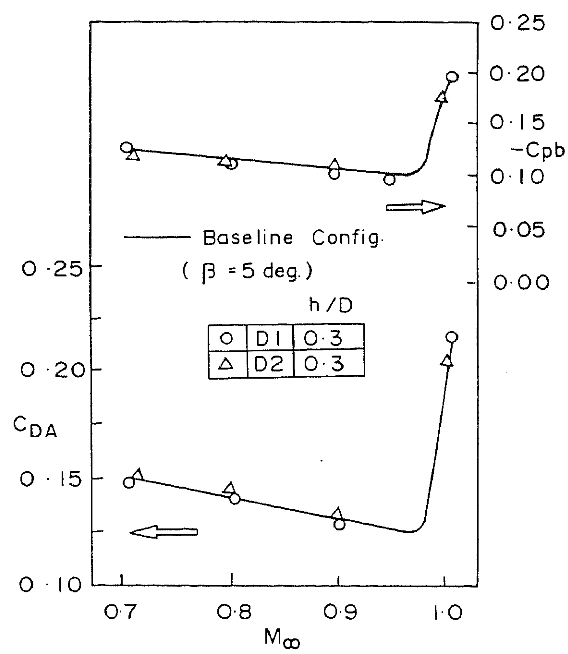

Fig. 9 Effects of cavity and ventilation for a boat-tailed base.

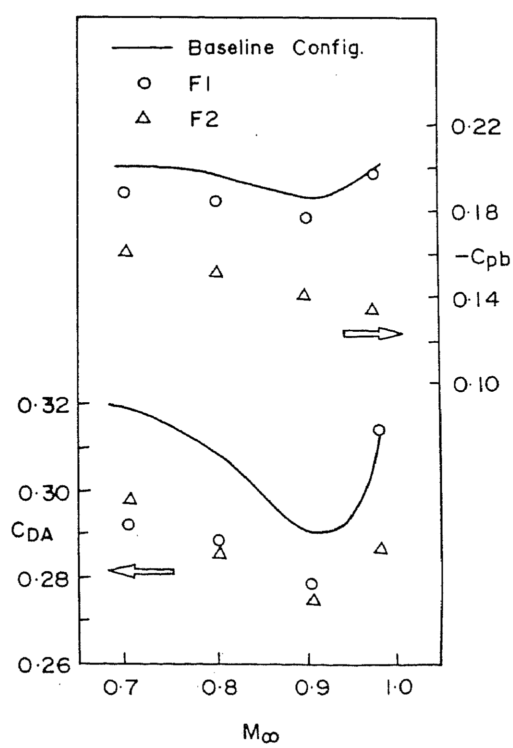

Fig. 10 Effects of cavity and ventilation for a flared base.

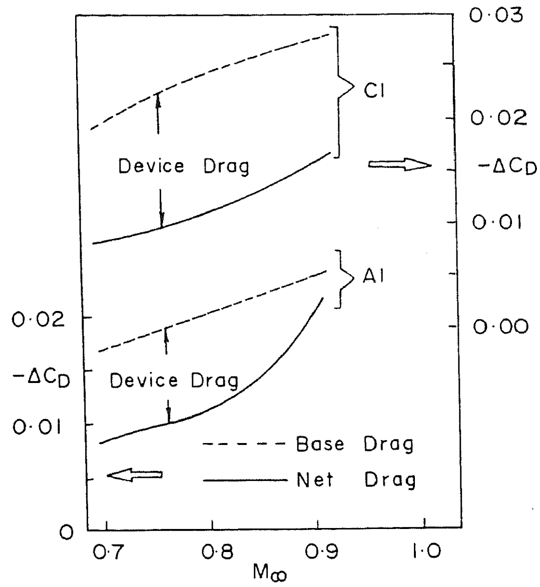

Fig. 11 Base and net drag reductions: configurations A1 and C1.

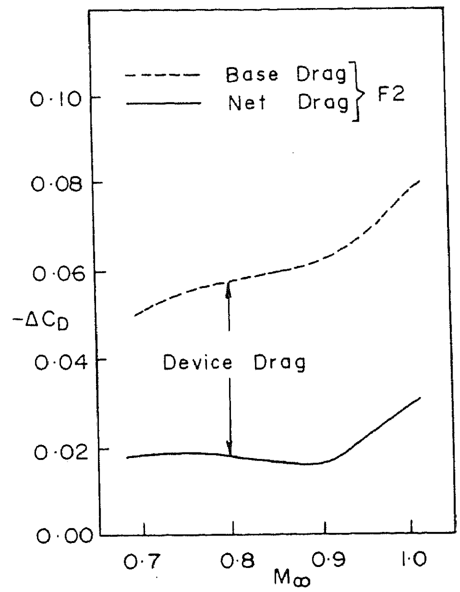

Fig. 13 Base and net drag reductions: configuration F2.

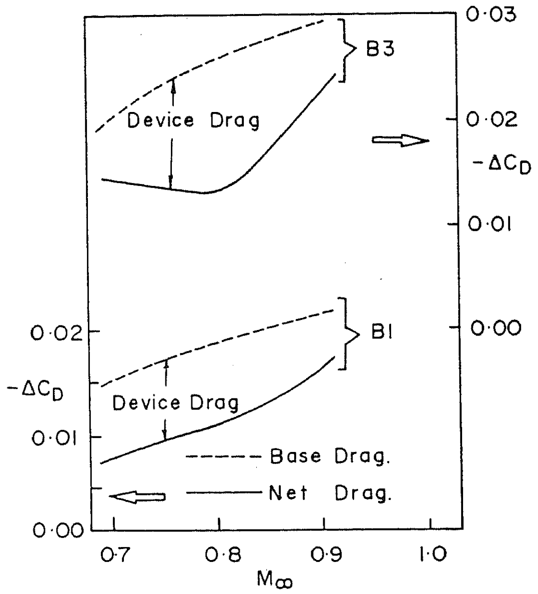

Fig. 12 Base and net drag reductions: configurations B1 and B3.

Reductions in base drag coefficients in the range of 0.015–0.03 may be seen for the cylindrical bases, with even higher benefits for the flared case. However,the net drag reductions are relatively lower for all cases due to the drag incurred by the devices. These drag reductions are comparable to those observed by Morel at low speeds. In the vicinity of $M_\infty = 1$, favorable effects of the devices seem to diminish (data not shown in Figs. 11 and 12), and the total drag is even slightly higher with the devices in some cases (Figs. 5, 6, and 8). No consistent picture seems to emerge with regard to the effectiveness of several devices examined around $M_\infty = 1$.

Physical Mechanisms Associated with Devices

Having seen the beneficial effects of several devices, a brief discussion on possible mechanisms that may be operating seem appropriate. With base cavities, depending on the depth, the vortex formation or shedding process may get pushed downstream (relative to the baseline configuration), thus reducing the influence at the base plane; also, the cavity could act as a geometrical constraint on the bubble motion. The base pressure correlation (Fig. 7) suggests that the dominant physical mechanism with ventilated cavities is the base bleed effect, which directly influences the mean flow in the base region. At low speeds, there is evidence[4] indicating suppression of vortex shedding to varying degrees for both short cavities ($h/D \approx 0.20$) and ventilated cavities. With regard to the two VSD's tested, it is believed that the likely major mechanism is the destruction of axisymmetry at the separation edge perhaps directly affecting the vortex formation/shedding process.

Conclusions

Effectiveness of several base modifications or passive devices for reducing axisymmetric base and total drag at transonic speeds has been assessed. While appreciable base drag reductions (as much as 15–20%) are possible with many of the devices examined, the net drag reductions, however, are relatively lower; the devices employed do incur losses. Even the relatively small total drag reductions observed are not insignificant from a design viewpoint. There is potential for optimizing the gains through a systematic parametric study involving one or more of the promising configurations studied here.

The devices examined have shown little effect when combined with boat-tailing, confirming further that boat-tailing is perhaps the most effective passive method of reducing base and afterbody drag. On the other hand, with a flared base, the favorable effects of the devices are quite impressive, as one might expect.

The results presented have clearly shown that base modifications, acting as near-wake manipulators, can be effective in the axisymmetric case and that drag reductions of engineering value can be realized.

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